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RECENT TEVATRON RESULTS ON CP-VIOLATION

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ABSTRACT

Using their full Tevatron Run II data sets, the CDF and D0 Experiments present measurements of CP-violating asymmetries in the charmless decays of bottom baryons $\Lambda_b^0 \to p\pi^-$, $\Lambda_b^0 \to pK^-$, and also for $B_s^0 \to K^-\pi^+$, $B^0 \to K^+\pi^-$, $D_s^\pm \to \phi\pi^\pm$, and for single muons and like-sign dimuons in $p\overline{p}$ collisions. Except for the like-sign dimuon asymmetry, these asymmetry measurements are consistent with available predictions of the standard model.

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1 Introduction

One of the great, outstanding mysteries of nature is that we observe a universe consisting of matter, rather than a very different type of universe consisting of equal quantities of matter and antimatter. The violation of Charge-Parity (CP) symmetry is a necessary ingredient [1] in producing such a matter-dominated universe. So far, small amounts of CP-violation have been observed only in the neutral kaon and neutral b-meson systems. CP-violation is included in the standard model (SM), which reproduces almost all observed particle physics processes. By searching for and measuring CP-violating processes and comparing with the SM predictions, we may open a window to observe additional CP-violation produced by other processes, or new physics, beyond the standard model.

Final results for the CP-violating asymmetries are presented for the full data sets for the CDF (9.3 fb^{-1}) and D0 (10.4 fb^{-1}) experiments. The Fermilab Tevatron produced $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV until its shutdown at the end of September, 2011. $p\overline{p}$ collisions are ideal for CP studies since the initial state is symmetrical between particle and anti-particles. The e^+e^- b-factories do not have the kinematic reach at reasonable luminosity to study the B^0_s system. Both the CDF II [2] and D0 [3] detectors are symmetric in η = -ln(tan($\theta/2$)) where θ is the polar angle of the produced particles relative to the proton beam direction, which gives equal acceptances even if there is a forward-backward production asymmetry for the detected final state. Both CDF and D0 detectors have silicon vertex detectors to study displaced vertices from decays of particles containing b- or c-quarks. In addition, the CDF II detector features a displaced vertex trigger and particle identification by energy loss dE/dx and time of flight TOF in the central drift chamber. CDF also can separate $\Lambda^0_b \to pK^-$ from $\overline{\Lambda^0_b} \to \overline{p}K^+$ by the kinematic momentum asymmetry $(p_+ - p_-)/(p_+ + p_-)$ between the positively and negatively charged particles in the decay. D0 features excellent muon identification using the muon toroid magnets and muon chambers and scintillators. D0 also regularly flips the polarities of the solenoid and toroid magnets independently, giving approximately equal integrated luminosities for all four configurations, which cancels many of the systematic, detector acceptance asymmetries.

The CP asymmetries are defined as the ratio of the difference divided by the sum of the rates Γ(particle$\to f$) and Γ(antiparticle$\to \overline{f}$) for processes involving particles and anti-particles:

$$A_{CP} = [\Gamma(b \to f) - \Gamma(\overline{b} \to \overline{f})]/[\Gamma(b \to f) + \Gamma(\overline{b} \to \overline{f})] = [N_{b\to f} - c_f * N_{\overline{b}\to\overline{f}}]/[N_{b\to f} + c_f * N_{\overline{b}\to\overline{f}}]$$

where $f(\overline{f})$ is the final state in the particle(antiparticle) decay. The raw number of observed particle and antiparticle events are corrected for detector efficiency ratio $c_f = \varepsilon(f)/\varepsilon(\overline{f})$ and detector related asymmetries to calculate A_{CP}.

2 CDF: A_{CP} in Charmless Decays of Bottom Hadrons

This study is motivated by possible new physics from internal penguin loops. The SM expects that $A_{CP}(B^0 \to K^+\pi^-)$ would equal $A_{CP}(B^+ \to K^+\pi^0)$. However, b-factory measurements [4, 5] find that these A_{CP}s are different by a 4-5 σ discrepancy. This $\Delta A_{B\to K\pi}$ puzzle may indicate incomplete understanding within the SM. Figure 1 shows the CDF [6] data fits. The results are presented in Table 1 and discussed below.

CDF finds a significantly non-zero $A_{CP}(B^0 \to K^+\pi^-)$ consistent with the measurements of LHCb [7], BaBar [8], and Belle [5].

Similarly CDF observes a significantly non-zero $A_{CP}(B^0_s \to K^-\pi^+) = [22 \pm 7(\text{stat.}) \pm 2(\text{syst.})]\%$, which is consistent with the LHCb measurement [7], and as expected by U-spin symmetry [9], is consistent with the direct, non-oscillated $A^{direct}_{CP}(B^0 \to \pi^+\pi^-)$ [10]. CDF's $A_{CP}(B^0_s \to K^-\pi^+)$ measurement is also consistent with the expected value by Gronau-Rosner-Lipkin scaling [11] according to the SM

$$A_{CP}(B^0_s \to K^-\pi^+) = -A_{CP}(B^0 \to K^+\pi^-) * \mathcal{B}(B^0 \to K^+\pi^-)/\mathcal{B}(B^0_s \to K^-\pi^+) * \tau(B^0_s)/\tau(B^0) \ .$$

The unique CDF [6] observations $A_{CP}(\Lambda^0_b \to p\pi^-) = [+6 \pm 7(\text{stat.}) \pm 3(\text{syst.})]\%$ and $A_{CP}(\Lambda^0_b \to pK^-) = [-10 \pm 8(\text{stat.}) \pm 4(\text{syst.})]\%$ are both consistent with zero, excluding large asymmetries. There are no SM calculations of comparable precision with which to compare.

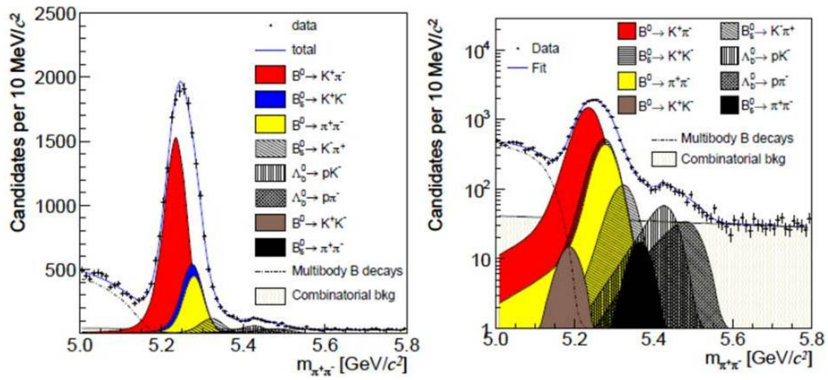

Figure 1: CDF fits to the two-body invariant mass distribution where the two final state particles are both assigned the pion mass. This shifts the mass peaks depending which particle is really a kaon or proton (antiproton) and on the mass of the parent particle, allowing the simultaneous fitting of the number of individual decay processes.

$A_{CP}(B^0 \to K^+\pi^-)$	SM predictions complicated by hadronic decays
$[-8.3 \pm 1.3(\text{stat.}) \pm 0.4(\text{syst.})]\%$	CDF (2014) [6]
$[-8.0 \pm 0.7(\text{stat.}) \pm 0.3(\text{syst.})]\%$	LHCb (2013) [7]
$[-10.7 \pm 1.6(\text{stat.}) \pm 0.5(\text{syst.})]\%$	BaBar (2013) [8]
$[-6.9 \pm 1.4(\text{stat.}) \pm 0.7(\text{syst.})]\%$	Belle (2013) [5]
$A_{CP}(B_s^0 \to K^-\pi^+)$	
$[22 \pm 7(\text{stat.}) \pm 2(\text{syst.})]\%$	CDF (2014) [6]
$[27 \pm 4(\text{stat.}) \pm 1(\text{syst.})]\%$	LHCb (2013) [7]
$[33 \pm 6(\text{stat.}) \pm 3(\text{syst.})]\%$	Belle (2013) [10] $A_{CP}^{direct}(B^0 \to \pi^+\pi^-)$ by U-spin symmetry [9]
$[31 \pm 5(\text{stat.+syst.})]\%$	SM scaling [11] $A_{CP}(B^0 \to K^+\pi^-)$ using PDG data [4]

Table 1: $A_{CP}(B^0 \to K^+\pi^-)$ and $A_{CP}(B_s^0 \to K^-\pi^+)$ for CDF and other experiments, by U-spin symmetry, and by Gronau-Rosner-Lipkin scaling.

3 D0: $A_{CP}(D_s^\pm \to \phi\pi^\pm)$

The SM predicts zero A_{CP} for the $D_s^\pm \to \phi\pi^\pm$ decay. By fitting the observed sum and difference of the number of observed D_s^+ and D_s^- events in Figure 2, D0 [12] finds $A_{raw}(D_s) = (-0.43 \pm 0.26)\%$. Correcting for the detector and background asymmetries $A_{KK} + A_\mu$ and the physics-driven $A_{physics}$ mainly due to the $B_s^0 - \overline{B_s^0}$ oscillation and the subsequent semileptonic decay $B_s^0 \to \mu^+\nu D_s^- X$

$$A_{CP}(D_s^\pm \to \phi\pi^\pm) = A_{raw} - A_{KK} - A_\mu - A_{physics} = [-0.38 \pm 0.26(\text{stat.}) \pm 0.08(\text{syst.})]\%,$$

which is consistent with the SM prediction of zero and greater than 3 times more sensitive than the earlier CLEO limit [13] of $[-0.5 \pm 0.8(\text{stat.}) \pm 0.4(\text{syst.})]\%$.

4 D0: Like-Sign Dimuon Charge Asymmetry

The SM produces like-sign $\mu^\pm\mu^\pm$ pairs from $B^0 - \overline{B^0}$ and $B_s^0 - \overline{B_s^0}$ mixing followed by semileptonic decays. CP-violating asymmetries would be produced if the rates of mixing differ $\Gamma(B^0 \to \overline{B^0}) \neq \Gamma(\overline{B^0} \to B^0)$ and/or $\Gamma(B_s^0 \to \overline{B_s^0}) \neq \Gamma(\overline{B_s^0} \to B_s^0)$. There is also a small CP-violating contribution from interference between mixed and direct decays to states accessible to both the particle and antiparticle parents such as B^0 or $\overline{B^0} \to D^{(*)+} + D^{(*)-}$ followed by $D^{(*)\pm} \to \mu^\pm X$ [14].

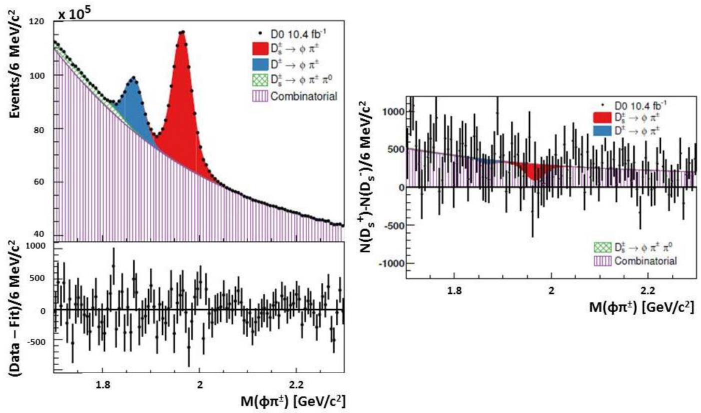

Figure 2: The $\phi\pi^{\pm}$ invariant mass distributions for the D0 Experiment. The upper-left panel shows the sum of the positively and negatively charged candidate events. The lower mass peak (blue) is due to the $D^{\pm}$ decays while the higher mass peak (red) is due to the $D_s^{\pm}$ meson decays. The lower-left panel shows the fit residuals for the sum distribution above. The right panel shows the fit to the differences between the numbers of candidate D_s^{+} and D_s^{-} mesons as function of the $\phi\pi^{\pm}$ mass.

The prior three D0 measurements at 1 fb^{-1} [15], 6.1 fb^{-1} [16], and 9 fb^{-1} [17] observed the like-sign dimuon charge asymmetry $A_{CP} = [\Gamma(\mu^+\mu^+) - \Gamma(\mu^-\mu^-)]/[\Gamma(\mu^+\mu^+) + \Gamma(\mu^-\mu^-)]$ to be inconsistent with the prediction of the SM at 1.7-3.9 σ significance. This D0 final measurement [18] includes the full 10.4 fb^{-1} Run II data sample and improved methodology and background subtraction which includes tighter track quality requirements and A_{CP} measurements for each of three bins in muon Impact Parameter (IP). Corrections were applied for measured charge-dependent asymmetries in efficiencies for detecting muons, and for pions and kaons faking muons.

Integrating over all IP, $|\eta|$, p_T bins, D0 measures the inclusive single muon charge asymmetry a_{CP} (all IP) $= [-0.032 \pm 0.042(\text{stat.}) \pm 0.061(\text{syst.})]\%$ which is consistent with the SM prediction of $a_{CP} \sim 10^{-5}$. The raw asymmetry a varies considerably and even changes sign over this range, giving confidence that no artificial asymmetry is introduced by the detector or analysis. The measured like-sign dimuon charge asymmetry dependence on the $(p_T, |\eta|)$ bins (summed over all IP) is shown in Figure 3. The final observed like-sign dimuon charge asymmetry is measured to be $A_{CP} = [-0.235 \pm 0.065(\text{stat.}) \pm 0.054(\text{syst.})]\%$ which is consistent with the three prior D0 measurements and represents a 3.6 standard deviation discrepancy significance from the SM prediction in Figure 3 and a 4.1 σ deviation from $A_{CP} = 0$.

The like-sign dimuon charge asymmetry for each kinematic (IP, $p_T, |\eta|$) bin is a linear function of the semileptonic charge asymmetries for $B^0 \to \mu^+ D^- X$ and $B_s^0 \to \mu^+ D_s^- X$ mesons, and the decay rate difference between the light and heavy components of the $B^0 - \overline{B^0}$ system

$$A_{CP} = C_d * a^d_{\text{sl}} + C_s * a^s_{\text{sl}} + C_\delta * \Delta\Gamma_{\text{d}}/\Gamma_{\text{d}}$$

where the linear coefficients C_d, C_s, and C_δ depend on the particular kinematic bin. These measured physics parameters are listed and plotted in Figure 4, showing consistency with prior D0 measurements of the a^d_{sl} [19] and a^s_{sl} [20] semileptonic decay asymmetries.

5 Summary

The recent Tevatron measurements of direct CP-violating asymmetries in charmless decays of bottom baryons and mesons by CDF and for $D^{\pm} \to \phi\pi^{\pm}$ by D0 are consistent with available SM predictions. All experiments find $A_{CP}(B^0 \to K^+\pi^-)$ to be quite significantly different from zero. The final D0 measurement of the CP-violating charge asymmetry of like-sign dimuons in $p\overline{p}$ collisions is still inconsistent with the SM prediction at the 3.6 standard deviation level, which represents one of the few such inconsistencies.

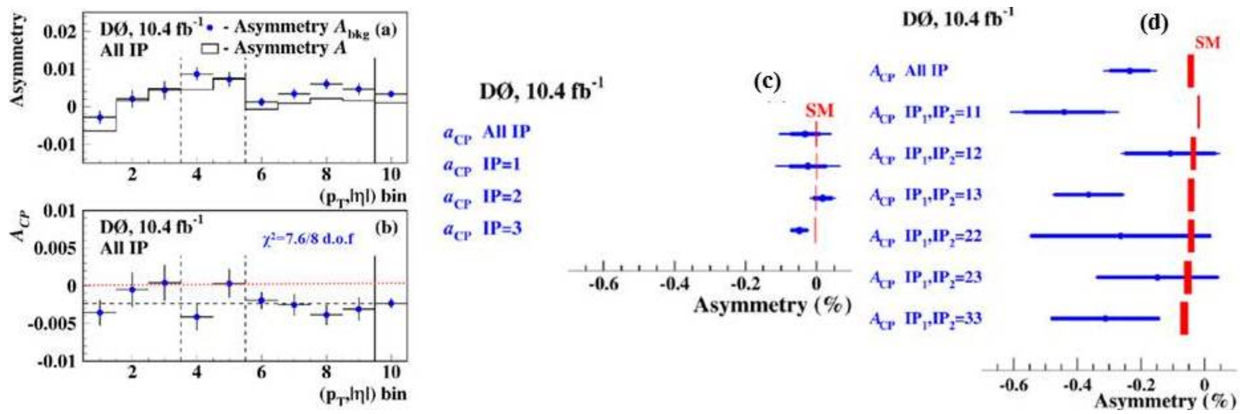

Figure 3: (a) The histogram is the raw asymmetry A, the data points are the measured detector-introduced background A_{bkg}; (b) $A_{CP} = A - A_{bkd}$ with the average A_{CP} value = dotted horizontal line and A_{CP} equal zero = red horizontal line. The bins 1-3 are for $|\eta| < 0.7$, bins 4-5 correspond to $0.7 < |\eta| < 1.2$, and bins 6-9 correspond to $1.2 < |\eta| < 2.2$ ranges for the dimuon pairs. The right-most bin #10 is integrated over all 9 $(p_T, |\eta|)$ bins and integrated over all IP; (c) The single muon charge asymmetry a_{CP} for different IP samples. The dashed line represents the SM prediction; (d) The like-sign dimuon asymmetry A_{CP} for different IP$_1$,IP$_2$ samples. The boxes show the SM prediction with the box width corresponding to the theoretical uncertainty.

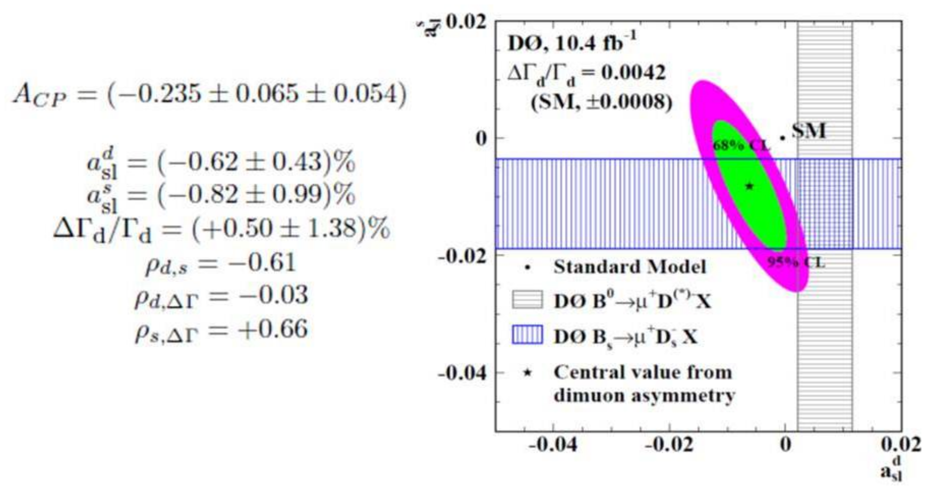

Figure 4: The D0 fitted parameters, including correlations, for the like-sign dimuon asymmetry. The figure shows the 68% and 95% confidence level contours in the $a^d_{\rm sl}$ - $a^s_{\rm sl}$ plane obtained from the fit of the inclusive single muon and like-sign dimuon asymmetries with fixed value of $\Delta\Gamma_{\rm d}/\Gamma_{\rm d}$ corresponding to the expected SM value [21]. Also shown are the prior D0 semileptonic measurements of $a^d_{\rm sl}$ [19] and $a^s_{\rm sl}$ [20], with bands representing ±1 standard deviation uncertainties of these measurements.

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